

Exploring A Rocket's Propulsion

A Science Brief With Exercise for Grades 6-12

Content Standards:

The following national standards for teaching science, mathematics, and technology are applicable to this exercise.

NS.5-8.1 and NS.9-12.1 SCIENCE AS INQUIRY

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

NS.5-8.2 and NS.9-12.2 PHYSICAL SCIENCE

- Properties and changes of properties in matter
- Motions and forces
- Transfer of energy

NS.5-8.5 and NS.9-12.5 SCIENCE AND TECHNOLOGY

- Abilities of technological design
- Understanding about science and technology

NT.K12.3 TECHNOLOGY PRODUCTIVITY TOOLS

- Students use technology tools to enhance learning, increase productivity, and promote creativity.
- Students use productivity tools to collaborate in constructing technology-enhanced models, prepares publications, and produce other creative works.

NM-NUM.6-8.3 and NM-NUM.9-12.3

- Compute fluently and make reasonable estimates

References

- Education Standards from Education-World.com
- Much of the introduction from HowStuffWorks.com



ACTIVITY – Trajectory as a Result of Decreasing Mass of Fuel

Objective:

Students will develop an understanding of rocket trajectory.
Students will develop an understanding of the effect of the decreasing mass of fuel on the rocket's acceleration.

Time:

One to two hours

Keywords:

Rocket, Propulsion, Acceleration, Conservation of Momentum, Approximation and Estimation

Materials:

Grades 5-8: Four-function calculator

Grades 9-10: Personal computer with a spreadsheet program

Grades 11-12: Personal computer with a high level programming language

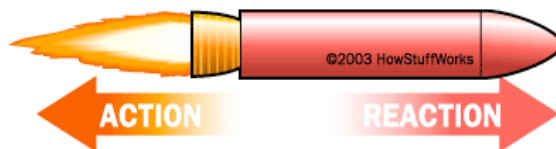
Background:

One of the most amazing endeavors man has ever undertaken is the exploration of space. A big part of the amazement is the complexity. Space exploration is complicated because there are so many problems to solve and obstacles to overcome. The biggest problem of all is harnessing enough energy simply to get a spaceship off the ground. That is where rocket engines come in.

Rocket engines are, on the one hand, so simple that you can build and fly your own model rockets very inexpensively. On the other hand, rockets are so complicated that only two countries have actually ever put people in orbit. The exercise in this lesson will help students understand a rocket's propulsion.

When most people think about motors or engines, they think about rotation. For example, the gasoline engine in a car produces rotational energy to drive the wheels. An electric motor produces rotational energy to drive a fan or spin a disk.

Rocket engines are fundamentally different. Rocket engines are **reaction** engines. The basic principle driving a rocket engine is Newton's famous principle that "to every action there is an equal and opposite reaction." A rocket engine is throwing mass in one direction and benefiting from the reaction that occurs in the other direction as a result.



This concept of "throwing mass and benefiting from the reaction" can be hard to grasp at first, because that does not seem to be what is happening. Rocket engines seem to be about flames and noise and pressure, not "throwing things." So let's look at a few examples to get a better picture of reality:

If you have ever shot a shotgun, especially a big 12-gauge shotgun, then you know that it has a lot of "kick." That is, when you shoot the gun it "kicks" your shoulder back with a great deal of force. That kick is a reaction. A shotgun is shooting about an ounce of metal in one direction at about 700 miles per hour, and your shoulder gets hit with the reaction. If you were wearing roller

skates or standing on a skateboard when you shot the gun, then the gun would be acting like a rocket engine and you would react by rolling in the opposite direction.

If you have ever seen a big fire hose spraying water, you may have noticed that it takes a lot of strength to hold the hose. The hose is acting like a rocket engine. The hose is throwing water in one direction, and the firefighters are using their strength and weight to counteract the reaction. If they were to let go of the hose, it would thrash around with tremendous force. If the firefighters were all standing on skateboards, the hose would propel them backwards at great speed!

When you blow up a balloon and let it go so that it flies all over the room before running out of air, you have created a rocket engine. In this case, what is being thrown is the air molecules inside the balloon. When you throw them out the nozzle of a balloon, the rest of the balloon reacts in the opposite direction.

Imagine the following situation: A boat gliding along a smooth lake firing cannonballs off the back. With each fire, the boat will react by moving in the opposite direction of the ball. The amount of speed the boat gains is determined by the **mass** of the cannonball and the **speed** of its fire. We say that the cannonball leaves with **momentum** equal to the product of the mass and speed. The principle of **Conservation of Momentum** then tells us that the boat must gain an equal momentum in the opposite direction. Leaving out the friction our boat experiences from wind resistance and drag against the water, we can calculate the speed the boat gains using the Conservation of Momentum. (See the procedure section below for the details)

Now the boat gets lighter with each fire of the canon, lighter by the mass of the cannonball that's sent off the back. The first cannonballs that are fired have to work both to speed up the boat and the cannonballs remaining on board, so the boat doesn't gain a lot of speed. As the load of cannonballs carried by the boat gets lighter, each fire of the canon can work more directly on the ship. For a rocket such as the Space Shuttle, the mass of the fuel (the cannonballs) is much greater than the mass of the ship (our boat) itself. This creates one of the interesting problems encountered by a rocket where you need a lot of fuel just to move the fuel.



You can see this weight equation very clearly on the Space Shuttle. If you have ever seen the Space Shuttle launch, you know that there are three parts:

- **The orbiter**
- **The big external tank**
- **The two solid rocket boosters**

The Orbiter weighs 165,000 pounds empty. The external tank weighs 78,100 pounds empty. The two solid rocket boosters weigh 185,000 pounds empty each. But then you have to load in the fuel. Each SRB holds 1.1 million pounds of fuel.

The external tank holds 143,000 gallons of liquid oxygen (1,359,000 pounds) and 383,000 gallons of liquid hydrogen (226,000 pounds). The whole vehicle -- shuttle, external tank, solid

rocket booster casings and all the fuel -- has a total weight of 4.4 million pounds at launch. 4.4 million pounds to get 165,000 pounds in orbit is a pretty big difference! To be fair, the orbiter can also carry a 65,000 pound payload (up to 15 x 60 feet in size), but it is still a big difference. The fuel weighs almost 20 times more than the Orbiter.

All of that fuel is being thrown out the back of the Space Shuttle at a speed of perhaps 6,000 mph (typical rocket exhaust velocities for chemical rockets range between 5,000 and 10,000 mph). The SRBs burn for about two minutes and generate about 3.3 million pounds of thrust each at launch (2.65 million pounds average over the burn). The three main engines (which use the fuel in the external tank) burn for about eight minutes, generating 375,000 pounds of thrust each during the burn.

What follows is an exercise using our hypothetical boat with a cannon to help make this situation clearer.

Facts You Need

The Law of Conservation of Momentum: Total momentum before equals total momentum after for any physical process. The momentum of any object is equal to its mass multiplied by its velocity.

Procedure

Using the attached worksheet, we are going to simulate our boat firing cannonballs off its back, calculating the change in the boat's speed through several fires of the cannon.

1. First decide on the starting values we need at the top of the worksheet. We need values for the mass of the boat and each cannonball, the number of cannonballs on board, the speed the cannon fires them, and the boat's initial speed (which you can just make 0 for the boat starting at rest). To make the calculations we'll do interesting and something like a real rocket, the mass of the cannonballs should be larger than the boat. For example, make the boat's mass 1000 kg with 10 cannonballs of mass 500 kg.
2. Fill down the column for **Cannon Fires** starting with 0 on the first line (for when the cannon hasn't been fired at all yet) down to the total number of cannonballs you decided on in step #1.
3. Fill down the column for **Cannonballs On Board** starting with the total number on the first line down to 0 for when all of the cannonballs have been fired.
4. Now we're ready to start across the first row, using the starting values you chose above:
 - a) In the **Mass of Boat + Cannonballs On Board Before Firing** column put the total mass of all the cannonballs added to the mass of the boat.
 - b) In the column **Boat's Speed Before Firing** just put the value you chose above.
 - c) Multiply those two to get the value for the next column for **Momentum of Boat + Cannonballs On Board Before Firing**.
 - d) After the cannon fires, the total mass of and in the boat is subtracted by the mass of one cannonball, so subtract that value from the value in the **Mass of Boat + Cannonballs On Board Before Firing** column for the **Mass of Boat + Cannonballs Remaining After Firing** column.
 - e) The cannonball fired takes away an amount of momentum equal to its mass multiplied by its firing velocity, so the **Momentum of Boat + Cannonballs. Remaining After Firing** is

- that subtracted from the value in the **Momentum of Boat + Cannonballs On Board Before Firing** column. (Why is this negative?)
- f) Now for the good part. We're ready to calculate the boat's new velocity for the **Boat's Speed After Firing** column by dividing the **Momentum of Boat + Cannonballs Remaining After Firing** value by the **Mass of Boat + Cannonballs Remaining After Firing**.
- g) For the **Change in Speed**, just subtract the **Boat's Speed Before Firing** from the **Boat's Speed After Firing**.
5. To complete the table, do the calculations for each row, adding up the total mass of and remaining on the boat for the **Mass of Boat + Cannonballs On Board Before Firing** column and using the value from **Boat's Speed After Firing** from the previous line for the new value of **Boat's Speed Before Firing** and then working across as in step 4.

Extensions

- Students who are familiar with spreadsheets through a program such as Excel can create a spreadsheet that will do all the calculations in the worksheet.
- Students familiar with a programming language such as Java or C++ can write a computer program that will do all the calculations in the worksheet.

